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# Measurement of the $\bar{B}_s^0$ effective lifetime in the $J/\psi f_0(980)$ final state

The LHCb collaboration<sup>†</sup>

## Abstract

The effective lifetime of the  $\bar{B}_s^0$  meson in the decay mode  $\bar{B}_s^0 \rightarrow J/\psi f_0(980)$  is measured using  $1.0 \text{ fb}^{-1}$  of data collected in  $pp$  collisions at  $\sqrt{s} = 7 \text{ TeV}$  with the LHCb detector. The result is  $1.700 \pm 0.040 \pm 0.026 \text{ ps}$  where the first uncertainty is statistical and the second systematic. As the final state is  $CP$ -odd, and  $CP$  violation in this mode is measured to be small, the lifetime measurement can be translated into a measurement of the decay width of the heavy  $\bar{B}_s^0$  mass eigenstate,  $\Gamma_H = 0.588 \pm 0.014 \pm 0.009 \text{ ps}^{-1}$ .

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The decay  $\bar{B}_s^0 \rightarrow J/\psi f_0(980)$ ,  $f_0(980) \rightarrow \pi^+ \pi^-$ , discovered by LHCb [1] at close to the predicted rate [2], is important for  $CP$  violation [3] and lifetime studies. In this Letter, we make a precise determination of the lifetime. The  $J/\psi f_0(980)$  final state is  $CP$ -odd, and in the absence of  $CP$  violation, can be produced only by the decay of the heavy (H), and not by the light (L),  $\bar{B}_s^0$  mass eigenstate [4]. As the measured  $CP$  violation in this final state is small [5], a measurement of the effective lifetime,  $\tau_{J/\psi f_0}$ , can be translated into a measurement of the decay width,  $\Gamma_H$ . This helps to determine the decay width difference,  $\Delta\Gamma_s = \Gamma_L - \Gamma_H$ , a number of considerable interest for studies of physics beyond the Standard Model [6]. Furthermore, this measurement can be used as a constraint in the fit that determines the mixing-induced  $CP$ -violating phase in  $\bar{B}_s^0$  decays,  $\phi_s$ , using the  $J/\psi \phi$  and  $J/\psi f_0(980)$  final states, and thus improve the accuracy of the  $\phi_s$  determination [5, 7]. In the Standard Model (SM)  $\phi_s = -2 \arg \left[ \frac{V_{ts} V_{tb}^*}{V_{cs} V_{cb}^*} \right]$ , if sub-leading penguin contributions are neglected, where the  $V_{ij}$  are the Cabibbo-Kobayashi-Maskawa matrix elements, which has a value of  $-0.036^{+0.0016}_{-0.0015}$  rad [8]. Note that the LHCb measurement of  $\phi_s$  [5] corresponds to a limit on  $\cos \phi_s$  greater than 0.99 at 95% confidence level, consistent with the SM prediction.

The decay time evolution for the sum of  $B_s^0$  and  $\bar{B}_s^0$  decays, via the  $b \rightarrow c\bar{c}s$  tree amplitude, to a  $CP$ -odd final state,  $f_-$ , is given by [9]

$$\Gamma(B_s^0 \rightarrow f_-) + \Gamma(\bar{B}_s^0 \rightarrow f_-) = \frac{\mathcal{N}}{2} e^{-\Gamma_s t} \left\{ e^{\Delta\Gamma_s t/2} (1 + \cos \phi_s) + e^{-\Delta\Gamma_s t/2} (1 - \cos \phi_s) \right\}, \quad (1)$$

where  $\mathcal{N}$  is a time-independent normalisation factor and  $\Gamma_s$  is the average decay width. We measure the *effective lifetime* by describing the decay time distribution with a single exponential function

$$\Gamma(B_s^0 \rightarrow f_-) + \Gamma(\bar{B}_s^0 \rightarrow f_-) = \mathcal{N} e^{-t/\tau_{J/\psi f_0}}. \quad (2)$$

Our procedure involves measuring the lifetime with respect to the well measured  $\bar{B}^0$  lifetime, in the decay mode  $\bar{B}^0 \rightarrow J/\psi \bar{K}^{*0}$ ,  $\bar{K}^{*0} \rightarrow K^- \pi^+$  (the inclusion of charge conjugate modes is implied throughout this Letter). In this ratio, the systematic uncertainties largely cancel.

The data sample consists of  $1.0 \text{ fb}^{-1}$  of integrated luminosity collected with the LHCb detector [10] in  $pp$  collisions at the LHC with 7 TeV centre-of-mass energy. The detector is a single-arm forward spectrometer covering the pseudorapidity range  $2 < \eta < 5$ , designed for the study of particles containing  $b$  or  $c$  quarks. The detector includes a high precision tracking system consisting of a silicon-strip vertex detector surrounding the  $pp$  interaction region, a large-area silicon-strip detector located upstream of a dipole magnet and three stations of silicon-strip detectors and straw drift-tubes placed downstream. Charged hadrons are identified using two ring-imaging Cherenkov detectors. Muons are identified by a muon system composed of alternating layers of iron and multiwire proportional chambers. The trigger consists of a hardware stage, based on information from the calorimeter and muon systems, followed by a software stage that applies a full event reconstruction.

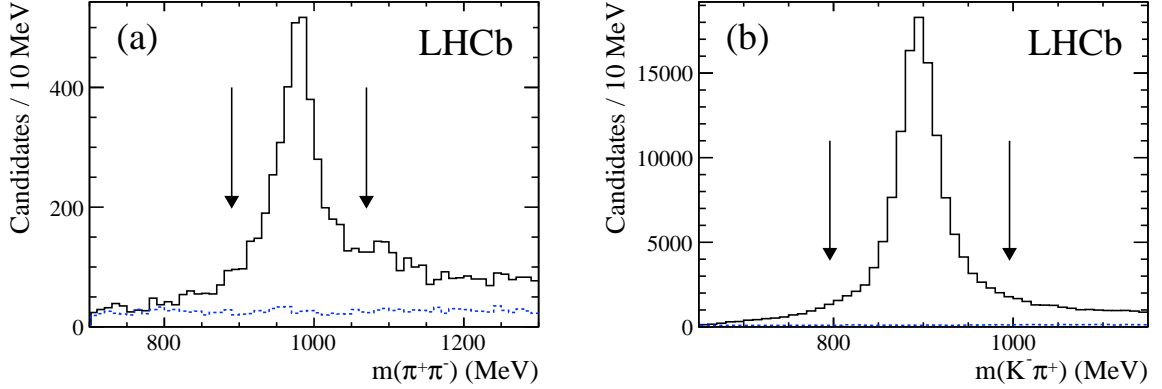


Figure 1: Invariant mass distributions of selected (a)  $\pi^+\pi^-$  and (b)  $K^-\pi^+$  combinations (solid histograms) for events within  $\pm 20$  MeV of the respective  $\bar{B}_s^0$  and  $\bar{B}^0$  mass peaks. Backgrounds (dashed histograms) are determined by fitting the  $J/\psi \pi^+\pi^-$  ( $J/\psi K^-\pi^+$ ) mass in bins of  $\pi^+\pi^-$  ( $K^-\pi^+$ ) mass. Regions between the arrows are used in the subsequent analysis.

The selection criteria we use for this analysis are the same as those used to measure  $\phi_s$  in  $\bar{B}_s^0 \rightarrow J/\psi \pi^+\pi^-$  decays [11]. Events are triggered by a  $J/\psi \rightarrow \mu^+\mu^-$  decay and a Boosted Decision Tree (BDT) [12] is used to set the  $J/\psi \pi^+\pi^-$  selection requirements. As the effective  $\bar{B}_s^0 \rightarrow J/\psi f_0(980)$  lifetime is measured relative to that of the decay  $\bar{B}^0 \rightarrow J/\psi \bar{K}^{*0}$ , we use the same trigger and BDT to select  $J/\psi K^-\pi^+$  events, except for the hadron identification that is applied independently of the BDT. The selected  $\pi^+\pi^-$  and  $K^-\pi^+$  invariant mass distributions, for candidates with  $J/\psi \pi^+\pi^-$  ( $J/\psi K^-\pi^+$ ) mass within  $\pm 20$  MeV (we work in units where  $c = \hbar = 1$ ) of the respective  $B$  mass peaks are shown in Fig. 1. The background distributions shown are determined by fitting the  $J/\psi \pi^+\pi^-$  ( $J/\psi K^-\pi^+$ ) mass distribution in bins of  $\pi^+\pi^-$  ( $K^-\pi^+$ ) mass. Further selections of  $\pm 90$  MeV around the  $f_0(980)$  mass and  $\pm 100$  MeV around the  $\bar{K}^{*0}$  mass are applied. The  $f_0(980)$  selection results in a  $\bar{B}_s^0 \rightarrow J/\psi f_0(980)$  sample that is greater than 99.4%  $CP$ -odd at 95% confidence level [13].

The analysis exploits the fact that the kinematic properties of the  $\bar{B}_s^0 \rightarrow J/\psi f_0(980)$  decay are very similar to those of the  $\bar{B}^0 \rightarrow J/\psi \bar{K}^{*0}$  decay. We can select  $B$  mesons in either channel using identical kinematic constraints and hence the decay time acceptance introduced by the trigger, reconstruction and selection requirements should almost cancel in the ratio of the decay time distributions. Therefore, we can determine the  $\bar{B}_s^0 \rightarrow J/\psi f_0(980)$  lifetime,  $\tau_{J/\psi f_0}$ , relative to the  $\bar{B}^0 \rightarrow J/\psi \bar{K}^{*0}$  lifetime,  $\tau_{J/\psi \bar{K}^{*0}}$ , from the variation of the ratio of the  $B$  meson yields with decay time

$$R(t) = R(0)e^{-t(1/\tau_{J/\psi f_0} - 1/\tau_{J/\psi \bar{K}^{*0}})} = R(0)e^{-t\Delta_{J/\psi f_0}}, \quad (3)$$

where the width difference  $\Delta_{J/\psi f_0} = 1/\tau_{J/\psi f_0} - 1/\tau_{J/\psi \bar{K}^{*0}}$ .

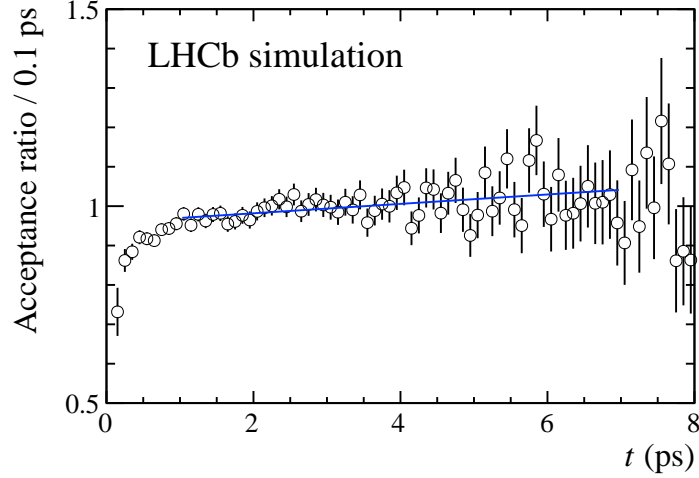


Figure 2: Ratio of decay time acceptances obtained from simulation between  $\bar{B}_s^0 \rightarrow J/\psi f_0(980)$  and  $\bar{B}^0 \rightarrow J/\psi \bar{K}^{*0}$  decays. The solid (blue) line shows the result of a linear fit.

We test the cancellation of acceptance effects using simulated  $\bar{B}_s^0 \rightarrow J/\psi f_0(980)$  and  $\bar{B}^0 \rightarrow J/\psi \bar{K}^{*0}$  events generated using PYTHIA 6.4 [14] with a specific LHCb configuration [15], where decays of hadronic particles are described by EVTGEN [16], and the LHCb detector simulation [17] based on GEANT4 [18]. Due to the selection requirements, the acceptances for both decay modes are equal to 0 at  $t = 0$ , after which there is a sharp increase, followed by a slow variation for  $t$  greater than 1 ps. Based on this, we only use events with  $t$  greater than 1 ps in the analysis. To good approximation, the acceptance ratio is linear between 1 and 7 ps, with a slope of  $a = 0.0125 \pm 0.0036 \text{ ps}^{-1}$  (see Fig. 2). We use this slope as a correction to Eq. 3 when fitting the measured decay time ratio

$$R(t) = R_0(1 + at)e^{-t\Delta_{J/\psi f_0}}. \quad (4)$$

Differences between the decay time resolutions of the decay modes could affect the decay time ratio. To measure the decay time resolution, we use prompt events containing a  $J/\psi$  meson. Such events are found using a dimuon trigger without track impact parameter requirements, plus two opposite-charged tracks with similar selection criteria as for  $J/\psi \pi^+ \pi^-$  ( $J/\psi K^- \pi^+$ ) events, apart from track impact parameter requirements, including that the  $J/\psi \pi^+ \pi^-$  ( $J/\psi K^- \pi^+$ ) mass be within  $\pm 20$  MeV of the  $\bar{B}_s^0$  ( $\bar{B}^0$ ) mass. These events are dominated by zero lifetime background. We use a triple-Gaussian function for the resolution model and find the average effective decay time resolution for  $\bar{B}_s^0 \rightarrow J/\psi f_0(980)$  and  $\bar{B}^0 \rightarrow J/\psi \bar{K}^{*0}$  decays to be  $41.0 \pm 0.9$  fs and  $44.1 \pm 0.2$  fs respectively, where the uncertainties are statistical only. This difference was found not to bias the decay time ratio using simulated experiments.

In order to determine the  $\bar{B}_s^0 \rightarrow J/\psi f_0(980)$  lifetime, we determine the yield of  $B$  mesons for both decay modes using unbinned maximum likelihood fits to the  $B$  mass



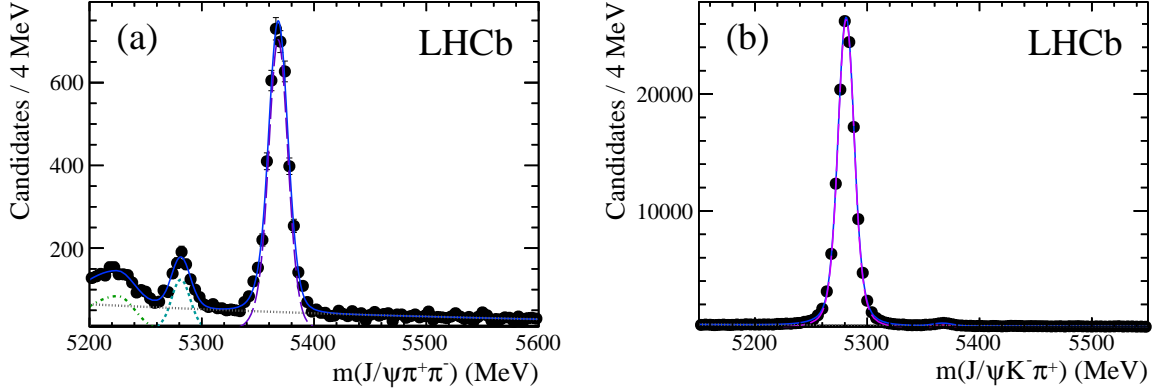


Figure 3: Invariant mass distributions of selected (a)  $J/\psi \pi^+ \pi^-$  and (b)  $J/\psi K^- \pi^-$  candidates. The solid (blue) curves show the total fits, the long dashed (purple) curves show the respective  $\bar{B}_s^0 \rightarrow J/\psi f_0(980)$  and  $\bar{B}^0 \rightarrow J/\psi \bar{K}^{*0}$  signals, and the dotted (grey) curve shows the combinatorial background. In (a) the short dashed (light blue) curve shows the  $\bar{B}^0 \rightarrow J/\psi \pi^+ \pi^-$  background and the dash dotted (green) curve shows the  $\bar{B}^0 \rightarrow J/\psi K^- \pi^+$  reflection. In (b) the short dashed (pink) curve shows the  $\bar{B}_s^0 \rightarrow J/\psi K^- \pi^+$  background.

distributions in 15 bins of decay time, of equal width between 1 and 7 ps. We perform a  $\chi^2$  fit to the ratio of the yields as a function of decay time and determine the relative lifetime according to Eq. 4. We obtain the signal and peaking background shape parameters by fitting the time-integrated dataset. In each decay time bin, we use these shapes and determine the combinatorial background parameters from the upper mass sidebands,  $5450 < m(J/\psi f_0) < 5600$  MeV and  $5450 < m(J/\psi \bar{K}^{*0}) < 5550$  MeV. With this approach, the combinatorial backgrounds are re-evaluated in each bin and we make no assumptions on the shape of the background decay time distributions. This method was tested with high statistics simulated experiments and found to be unbiased.

The time-integrated fits to the  $J/\psi f_0(980)$  and the  $J/\psi \bar{K}^{*0}$  mass spectra are shown in Fig. 3. The signal distributions are described by double Crystal Ball functions (sums of two Crystal Ball functions [19] with equal means but tails on opposite sides) and the combinatorial backgrounds by exponential functions. All parameters are determined from data. There are  $4040 \pm 75$   $\bar{B}_s^0 \rightarrow J/\psi f_0(980)$  and  $131\,920 \pm 400$   $\bar{B}^0 \rightarrow J/\psi \bar{K}^{*0}$  signal decays. The decay time distributions, determined using fits to the invariant mass distributions in bins of decay time as described above, are shown in Fig. 4. These are made by placing the fitted signal yields at the average  $\bar{B}^0 \rightarrow J/\psi \bar{K}^{*0}$  decay time within the bin rather than at the centre of the decay time bin. This procedure corrects for the exponential decrease of the decay time distributions across the bin. The subsequent decay time ratio distribution is shown in Fig. 5, and the fitted reciprocal lifetime difference is  $\Delta_{J/\psi f_0} = -0.070 \pm 0.014 \text{ ps}^{-1}$ , where the uncertainty is statistical only. Taking  $\tau_{J/\psi \bar{K}^{*0}}$  to be the mean  $\bar{B}^0$  lifetime  $1.519 \pm 0.007$  ps [20], we determine  $\tau_{J/\psi f_0} = 1.700 \pm 0.040$  ps.

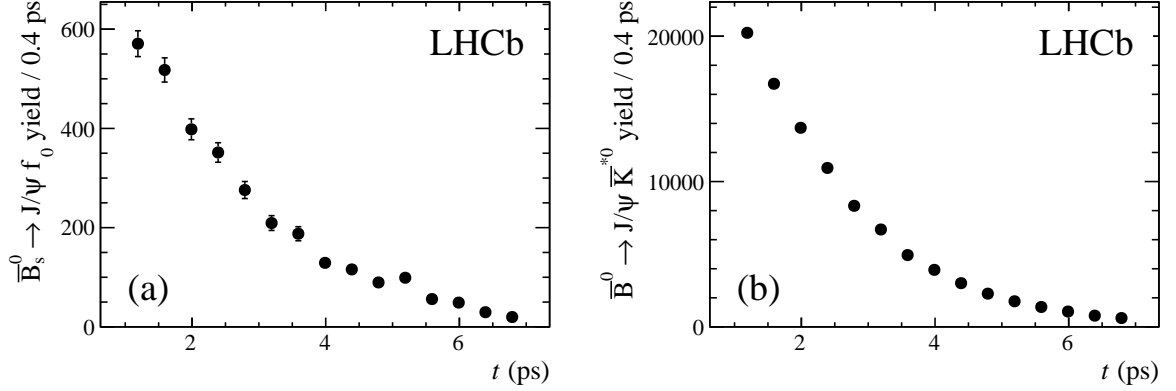


Figure 4: Decay time distributions for (a)  $\bar{B}_s^0 \rightarrow J/\psi f_0(980)$  and (b)  $\bar{B}^0 \rightarrow J/\psi \bar{K}^{*0}$ . In (b) the error bars are smaller than the points.

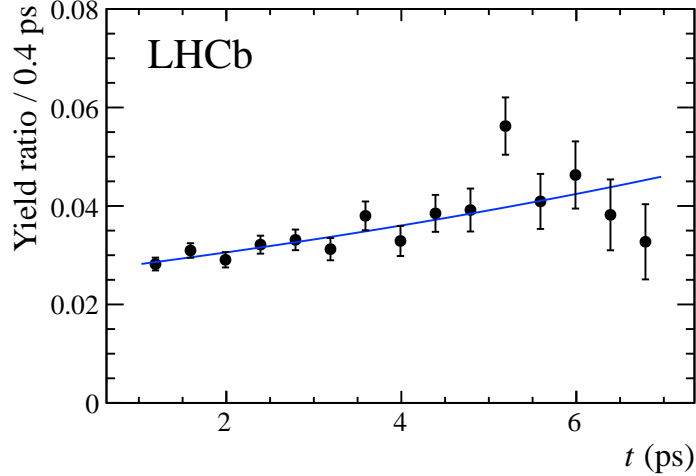


Figure 5: Decay time ratio between  $\bar{B}_s^0 \rightarrow J/\psi f_0(980)$  and  $\bar{B}^0 \rightarrow J/\psi \bar{K}^{*0}$ , and the fit for  $\Delta_{J/\psi f_0}$ .

Sources of systematic uncertainty on the  $\bar{B}_s^0 \rightarrow J/\psi f_0(980)$  lifetime are investigated and listed in Table 1. We first investigate our assumptions about the signal and combinatorial background mass shapes. The relative change of the determined  $\bar{B}_s^0 \rightarrow J/\psi f_0(980)$  lifetime between fits with double Crystal Ball functions and double Gaussian functions for the signal models is 0.001 ps, and between fits with exponential functions and straight lines for the combinatorial background models is 0.010 ps. The different particle identification criteria used to select  $\bar{B}_s^0 \rightarrow J/\psi f_0(980) \rightarrow \mu^+ \mu^- \pi^+ \pi^-$  and  $\bar{B}^0 \rightarrow J/\psi \bar{K}^{*0} \rightarrow \mu^+ \mu^- K^- \pi^+$  decays could affect the acceptance cancellation between the modes. In order to investigate this effect, we loosen and tighten the particle identification selection for the kaon and repeat

Table 1: Summary of systematic uncertainties on the  $\bar{B}_s^0 \rightarrow J/\psi f_0(980)$  effective lifetime.

Source	Uncertainty (ps)
Signal mass shape	0.001
Background mass shape	0.010
Kaon identification	0.007
Acceptance	0.018
Statistical bias	0.012
$CP$ -even component	0.001
$\bar{B}^0$ lifetime [20]	0.009
Sum in quadrature	0.026

the analysis. The larger difference with respect to the default selection, 0.007 ps, is assigned as a systematic uncertainty. We also assign half of the relative change between the fit without the acceptance correction and the default fit, 0.018 ps, as a systematic uncertainty. Potential statistical biases of our method were evaluated with simulated experiments using similar sample sizes to those in data. An average bias of 0.012 ps is seen and included as a systematic uncertainty. The observed bias vanishes in simulated experiments with large sample sizes. As a cross-check, the analysis is performed with various decay time bins widths and fit ranges, and consistent results are obtained. The possible  $CP$ -even component, limited to be less than 0.6% at 95% confidence level [13], introduces a 0.001 ps systematic uncertainty. Using the PDG value for the  $\bar{B}^0$  lifetime as input requires the propagation of its error as a systematic uncertainty. All the contributions are added in quadrature and yield a total systematic uncertainty on the lifetime of 0.026 ps (1.5%). Thus the effective lifetime of the  $J/\psi f_0(980)$  final state in  $\bar{B}_s^0$  decays, when describing the decay time distribution as a single exponential is

$$\tau_{J/\psi f_0} = 1.700 \pm 0.040 \pm 0.026 \text{ ps} . \quad (5)$$

Given that  $\phi_s$  is measured to be small, and the decay is given by a pure  $b \rightarrow c\bar{c}s$  tree amplitude, we may interpret the inverse of the  $\bar{B}_s^0 \rightarrow J/\psi f_0(980)$  effective lifetime as a measurement of  $\Gamma_H$  with an additional source of systematic uncertainty due to a possible non-zero value of  $\phi_s$ . For  $\cos \phi_s = 0.99$ ,  $\Gamma_s = 0.6580 \text{ ps}^{-1}$  and  $\Delta\Gamma_s = 0.116 \text{ ps}^{-1}$  [5],  $\tau_{J/\psi f_0}$  changes by 0.002 ps. This is added in quadrature to the systematic uncertainties on  $\tau_{J/\psi f_0}$  to obtain the final systematic uncertainty on  $\Gamma_H$ .

In summary, the effective lifetime of the  $\bar{B}_s^0$  meson in the  $CP$ -odd  $J/\psi f_0(980)$  final state has been measured with respect to the well measured  $\bar{B}^0$  lifetime in the final state  $J/\psi \bar{K}^{*0}$ . The analysis exploits the kinematic similarities between the  $\bar{B}_s^0 \rightarrow J/\psi f_0(980)$  and  $\bar{B}^0 \rightarrow J/\psi \bar{K}^{*0}$  decays to determine an effective lifetime of

$$\tau_{J/\psi f_0} = 1.700 \pm 0.040 \pm 0.026 \text{ ps},$$

corresponding to a width difference of

$$\Delta_{J/\psi f_0} = -0.070 \pm 0.014 \pm 0.001 \text{ ps}^{-1},$$

where the uncertainties are statistical and systematic respectively. This result is consistent with, and more precise than, the previous measurement of  $1.70^{+0.12}_{-0.11} \pm 0.03 \text{ ps}$  from CDF [21]. Interpreting this as the lifetime of the heavy  $\bar{B}_s^0$  eigenstate, we obtain

$$\Gamma_H = 0.588 \pm 0.014 \pm 0.009 \text{ ps}^{-1}.$$

This value of  $\Gamma_H$  is consistent with the value  $0.600 \pm 0.013 \text{ ps}^{-1}$ , calculated from the values of  $\Gamma_s$  and  $\Delta\Gamma_s$  in Ref. [5].

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